Appendix F
New Accelerator(s)

The U.S. Department of Energy (DOE) has determined that accelerators could be used for the production of medical and industrial isotopes, the conversion of neptunium-237 to plutonium-238, and to support nuclear energy research and development initiatives. The production of medical and industrial isotopes that are neutron poor could be effectively accomplished using a low-energy accelerator with energies in the range of 30 million to 70 million electron volts. Isotopes that are neutron rich are made in either reactors or high-energy-accelerator spallation neutron sources. The irradiation of neptunium-237 targets for plutonium-238 production can be effectively accomplished using a high-energy accelerator with energies much greater than 100 million electron volts. Both low- and high-energy accelerators can be used to support nuclear energy research and development initiatives.

The accelerator(s) would be constructed and operated at one or two DOE sites where security measures would be in place, including access control and procedures, to ensure the adequate protection of all materials processed and stored. Although each accelerator would be independent of the other for the performance of its mission and can therefore be separately located, there may be important efficiencies to be gained by their colocation at the same DOE site.

F.1 LOW-ENERGY ACCELERATOR

A new 70-million-electron-volt cyclotron can be used for the production of medical and industrial isotopes and to support nuclear energy research and development initiatives. Important uses of the cyclotron would be to:

- Serve as a user facility for radioisotope production research, including excitation function measurements, high-power-density targetry required for isotope production at high beam currents, radiochemical separations, and purification

- Provide research capability for the development and evaluation of next-generation radioisotopes and radiopharmaceuticals for applications to imaging and therapy

- Provide a state-of-the-art, dedicated, multipurpose isotope production facility with simultaneous multiuser capability

- Respond to the national need for a continuous and reliable supply of present and future radioisotopes for biomedical research and other applications

- Provide a training facility for the next generation of nuclear/radiochemists in the areas of: nuclear and radiochemical techniques for radionuclide production, separation, and purification; radiotracer syntheses; radiopharmaceuticals development and evaluation; radiation protection and safety; and application of radiotracer methodology for biomedical investigations

Three low-energy accelerator options would be available for the production of medical and industrial isotopes and to support nuclear energy research and development: (1) a high-current proton linear accelerator (linac), (2) a multiparticle cyclotron, or (3) a proton-only cyclotron. The proton-only cyclotron would have distinct technical advantages over the other two options and is described further in the sections that follow.

F.1.1 Overview

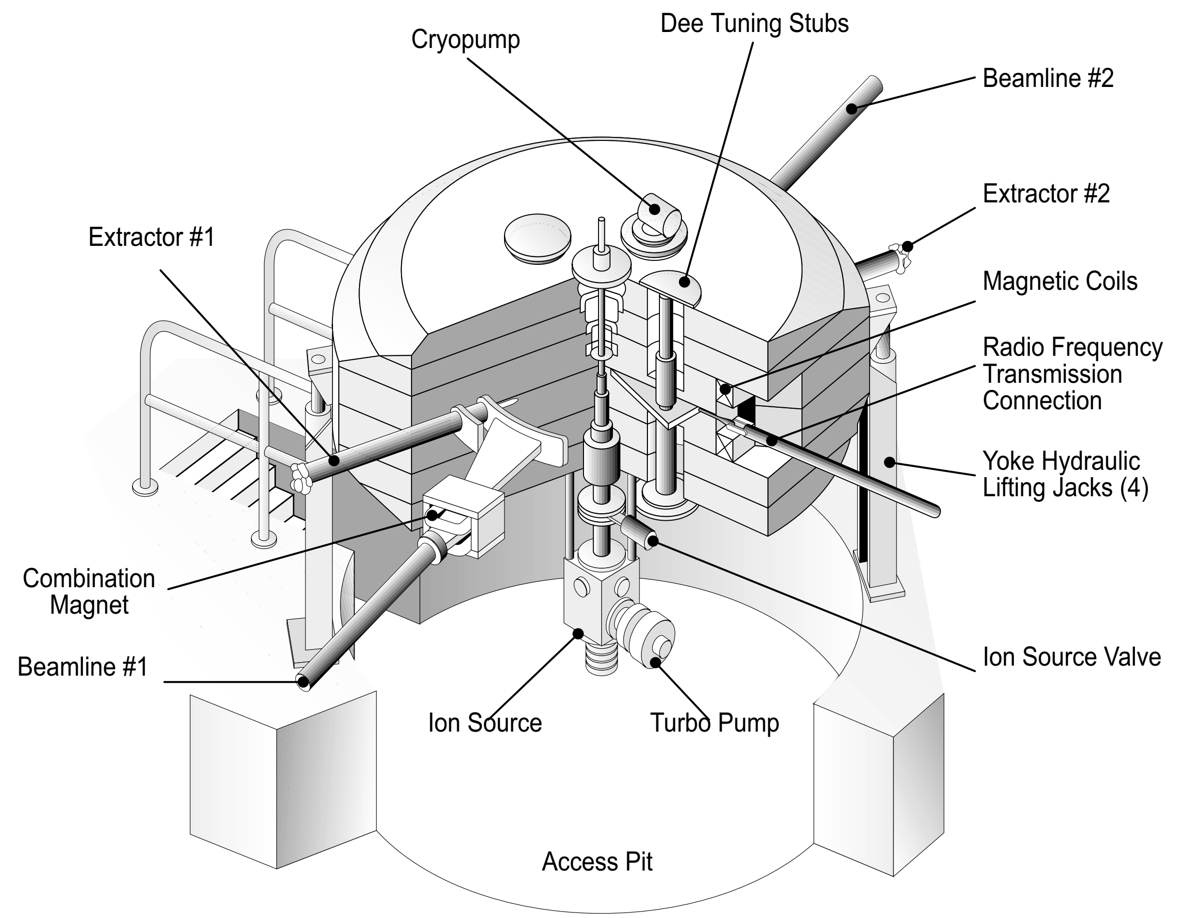
The proton-only cyclotron can be either positive proton or negative ion and is referred to as a proton cyclotron H^+ or proton cyclotron H^-. The alternative of a positive proton cyclotron would offer lower vacuum requirements and, with the latest technology, high-extraction efficiency can be achieved. But, obtaining variable energy output would be complicated, extraction can be into only a single port, and splitting the beam would require a complicated septum magnet. In comparison, the negative ion cyclotron would offer continuous beam with high-current capacity using very simple high-efficiency extraction, a simple method to vary the particle energy, and the possibility of simultaneous irradiation of two different target arrays at different energies. The high-extraction efficiency would be achieved simply by passing the negatively charged beam through a thin foil that strips the electrons from the ion, creating a positive proton. The proton would be directly ejected from the machine by the existing magnetic field with high efficiency (greater than 98 percent). This feature would be important to minimize the activation of the cyclotron structure and thus reduce radiation exposure to the operational staff.

High-beam current would be advantageous because more products can be prepared in a shorter time. In addition, a much higher specific-activity radioisotope can be prepared at the higher-beam current of the cyclotron. Specific activity is the ratio of radioactive atoms to total atoms of the same atomic number in the sample and is expressed in units of curies per gram. A stable element can enter the process in many ways, most commonly from the target, the reagents, or from the environment during handling of the irradiated target and subsequent processing. These quantities tend to be fairly constant from run to run, and would be independent of irradiation time or beam current. Therefore, a higher-intensity beam generally makes more radioactivity without adding to the amount of stable element in the final product. Specific activity is often a critical parameter in many nuclear medicine applications, including research and clinical use.

The cyclotron can also continuously tune the beam energy, which would be an advantage for research. The ability to tune the energy with precision can also help achieve high-purity isotope production by avoiding energies where impurity isotopes would be readily co-produced. It would be desirable to precisely tune to a low energy to achieve optimal production of certain radioisotopes. Energy variability from 40 million to 70 million electron volts would be easy, 30 million to 70 million electron volts would be possible, and 20 million to 70 million electron volts would need some design effort. It also would be possible to strip only part of the beam in an orbit and have another stripper at 180 degrees to simultaneously extract a second beam. This beam can have the same or different energy and intensity as the first. These are important advantages for flexibility in research isotope production and are within the capabilities of commercially proven technology.

F.1.2 Isotope Production Systems Design

A new building would be constructed to house the cyclotron and the four beam lines. The walls of the facility would be 4.6 meters (15 feet) thick behind the target stations to minimize the neutron flux outside the building. The walls surrounding the cyclotron itself would be 3 meters (10 feet) thick. The mazes throughout the building in general would have walls 1.5 meters (5 feet) thick, so that the total thickness surrounding the cyclotron area would be 3 meters (10 feet). The beam would be diverted to the four target stations by switching magnets located in the cyclotron vault. The beam would be directed through focusing and steering magnets to the target. In the isotope production beam line (northwest cave), the targets would be installed and removed vertically from a hot cell, which would be located on the second floor directly above the target station. The power supplies for the magnets would be housed with the power supplies for the cyclotron. The mechanical equipment for cooling water would be housed in a shielded mechanical room adjacent to the cyclotron vault. Recirculating water for cooling of the targets and systems that could contain potentially radioactive material would be separated to prevent cross-contamination. These systems would be contained in mechanical equipment rooms near the respective target station. Piping would be contained in waterproof trenches with leak detection. Isometric views of the new cyclotron and beam lines are shown in **Figures F–1** and **F–2**.



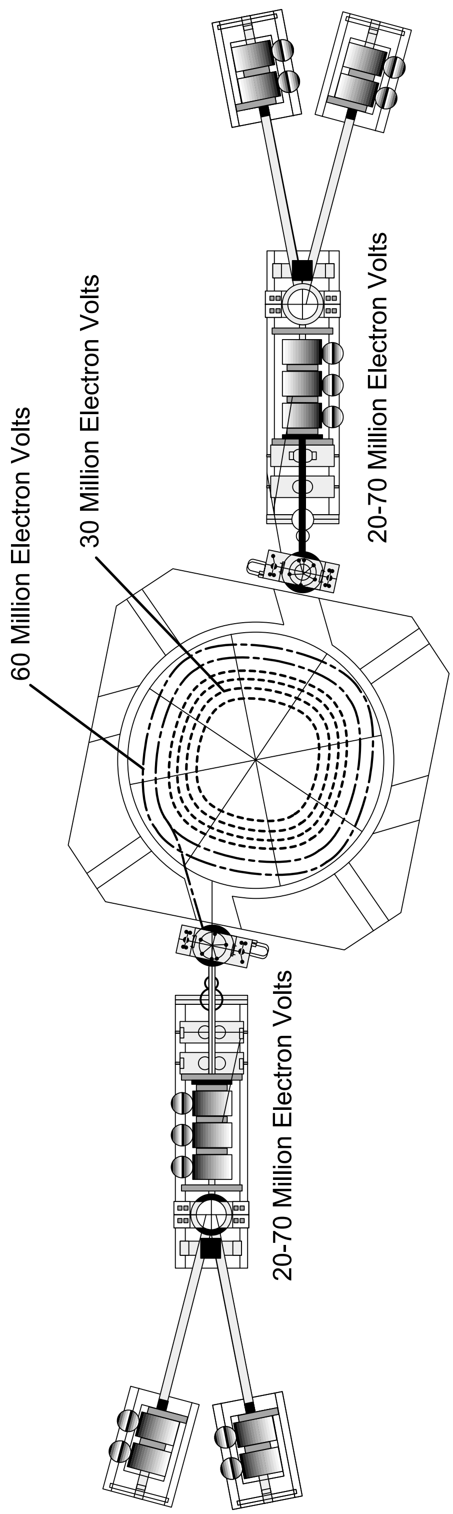
Source: TechSource 2000.

Figure F–1 Isometric View of the New Cyclotron

The isotope production system would be divided into several sections. These are the beam lines out of the cyclotron, the beam lines into each of the target caves, and the target holders and handling system in each of the target caves.

F.1.2.1 Beam Line Design

The beam would be extracted from the cyclotron by means of a thin carbon foil that strips two electrons off the hydrogen minus one ion (H^-) and would convert the negatively charged hydrogen ions to positively charged ions. These would be bent in the opposite direction in the magnetic field of the cyclotron. Once the beam has been extracted from the cyclotron, it would pass through a beam shutter and into a quadrupole-focusing magnet. After the beam passes through the focusing magnet, it would pass into the switching magnet that



Source: TechSource 2000.

Figure F–2 Cyclotron and Beam Lines

would bend the beam into either one of the two beam lines located on each end of the facility. After passing through the switching magnet, the beam would pass through another set of focusing and steering magnets inside the cyclotron vault and through the wall into the target cave. The direct current quadrupole magnets and dipole magnets would be of conventional design and would have pole tip fields that are easily achievable with standard designs. In addition, the beam line for the northwest target cave would have a raster scan system consisting of variable-field horizontal and vertical steering magnets. This would allow rapid sweeping of the beam spot across the target face. Magnet cooling would require high-resistivity deionized water for voltage standoff purposes.

The vacuum system consists of beam pipes, bellows and flanges, vacuum valves and actuators, vacuum pumps, and vacuum instrumentation. The valves for the facility would include gate valves for isolating sections of lines, a fast valve for isolating the cyclotron vacuum volumes from the beam lines in the event of a target window failure, and roughing valves at the cryopumps.

The beam diagnostics system would provide the information needed to monitor and control beam position throughout the beam lines and on the targets, and final spot size on the target. Adjusting the fields of the direct current bending magnets would control the coarse beam position. Varying the steering magnet fields would make fine adjustments in the beam position. Adjusting the final quadrupole magnets in the line would control the beam spot size on the target. Each beam line would be equipped with a beam scanner that would give a distribution profile of the beam in both horizontal and vertical directions.

F.1.2.2 Isotope Production Equipment

There would be three separate target systems set up in this facility. The first would be the radioisotope production system housed in the northwest target cave. The second would be the positron emission tomography radioisotope production system housed in the southwest target cave. The third would be the research target system housed in the southeast target cave.

F.1.2.2.1 High-Level Radioisotope Production—Northwest Target Cave

SYSTEM FUNCTION

The isotope production equipment would include several components: the target housing (with targets), target transfer mechanisms, a hot cell, and a target radiation shield. All of these components would be located in the lower level of the facility except for the hot cell and portions of the target transfer mechanisms. Collectively, these systems must provide for target irradiations in safe, cost-effective, and environmentally conscious manners.

SYSTEM DESIGN BASIS

The system would be designed to accept a proton beam with nominal energies of 30 million to 70 million electron volts and a maximum average beam current of 1 milliampere. Normal operations would be expected to use 250 microamperes to 500 microamperes of beam current. Target shielding would be sized to accommodate up to 1 milliampere of beam current, since the cyclotron would be capable of delivering currents of up to 2 milliamperes.

Targets would be designed with a circular cross section. Calculations of power deposition would assume a flat beam profile over the entire target surface. A rastering system would be in place on this beam line to ensure an optimum distribution of the beam. More than one target would be irradiated at a time, but the targets would be inserted and retrieved as a single assembly. The thickness of this assembly must be at least

10 centimeters (3.9 inches), not including water gaps between the target faces. This ensures that there would always be enough target material or water to stop 70 million-electron-protons.

The target housing would become very highly activated during the irradiation process. Therefore, personnel would not have access to the target housing after the initial irradiation. In addition, a concrete radiation shield would be installed downstream of the target assembly inside the cave to provide extra shielding from forward-going prompt neutrons and from residual gamma radiation.

SYSTEM DESIGN DESCRIPTION

The isotope production target facility would be housed in a stainless steel cylinder, which would form a 5.5-meter (18-foot) column of water. The top of the tank would open to a hot cell. The bottom of the tank would connect to the beam vacuum chamber. A beam of protons ranging from 30 million to 70 million electron volts would enter the water column through a thin vacuum window at the end of the beam vacuum chamber. The targets would be transported by a trolley holder, which would use a rectangular tube as a track. The rectangular track would be housed within the 5.5-meter (18-foot) water column. The trolley would transport and locate the targets at the beam centerline just downstream of the beam vacuum chamber exit window. The trolley drive system would be a semi-automatic motor-driven chain-cable assembly. The target would be water-cooled by forced water traveling vertically over the face of the target.

The water column would house the target transport system and contain the cooling water. The diameter of the water column would be sufficient to stop protons with energies up to 70 million electron volts. The 5.5-meter (18-foot) height also would provide neutron shielding in the vertical direction. The target water column would be constructed from nuclear-grade, corrosion-resistant material. The column would have inlet and outlet connections for cooling water and a connection for the beam pipe. All the connections would be as-low-as-is-reasonably-achievable-designed to reduce radiation exposure during maintenance or removal of the system. The bottom of the column would form a plenum where the cooling water inlet would be. On the top of the plenum, there would be alignment holes to align the target drive track system. Above the beam line vacuum chamber connection would be the cooling water outlet. The top of the column would penetrate the hot cell to approximately tabletop height. There would be a lid at the top of the column to prevent objects from falling down the column and to reduce radioactive airborne emissions. All water line connections and seals would be made of nuclear-grade material.

At the downstream end of the beam line vacuum chamber would be a thin window. The window would be designed to permit the beam to irradiate the production targets with minimal beam loss. The window would be made of high-strength, nuclear-grade, corrosion-resistant material. The exit window would be designed for quick replacement in the event of a failure.

The targets would be transported vertically to and from the hot cell to the beam line within the water column. The targets would be transported using a motor-driven chain and cable assembly. The chain-cable assembly would be a continuous loop attached to a trolley. The top half of the loop would be a chain for a slip-free connection to the drive motor via the sprocket. The bottom half of the loop would be a cable. The track system for the target transport would be a rectangular tube that would guide and align the trolley. The track system would be removable from the hot cell for replacement or repair. The track would be aligned to the beam centerline by engagement of alignment holes located at the bottom of the water column. A trolley target holder would be attached to the chain-cable assembly and used to transport the targets in the rectangular track. The target holder would be capable of holding targets of various thicknesses in a horizontal array. The targets would be separated in the array by flowing water coolant to allow cooling of both the front and back faces of the target. To insert and remove the targets one at a time from the target trolley holder, a target extraction system would be needed. The extraction system would be installed in the hot cell and would be motorized to simplify the manipulation of the targets from within the hot cell.

The target assembly would consist of the target material housed in a sealed container. The container would be constructed from material designed to withstand corrosion by either the water coolant or the target material. The sealed container would be a circular disc, fabricated in a variety of thicknesses. The targets would be water-cooled. The water coolant would enter the water column at the bottom into the plenum, pass through a fixed orifice into the target track system, flow vertically across the targets, and then exit the water column above the beam centerline. The targets would be placed in the beam line tilted at 30 degrees. This would reduce the heat flux at the target front and back faces, allow for a larger cooling channel across the target, hence more water flow, and would reduce the thickness of the target, thus reducing the heat path to the water coolant.

F.1.2.2.2 Positron Emission Tomography Radioisotope Production—Southwest Target Cave

SYSTEM FUNCTION

The isotope production equipment would include several components: the automatic target changer (with targets), the water cooling system, the helium cooling system for the front foil of the targets, and the radioisotope removal system and transport line. Collectively, these systems must provide for target irradiations in safe, cost-effective and environmentally conscious manners.

SYSTEM DESIGN BASIS

The system would be designed to accept a proton beam with a nominal energy of 30 million to 70 million electron volts and a maximum average beam current of 250 microamperes. Targets would be designed with a circular cross section with a minimum diameter of 2.5 centimeters (1 inch). Calculations of power deposition would assume either a Gaussian beam energy density profile, with a minimum full-peak width at half maximum of 1 centimeter (0.34 inch). One target would be irradiated at a time, but several targets would be present in the vault at a single time in an automatic target changer. The targets would be inserted and retrieved remotely. The target housing would become activated during the irradiation process.

SYSTEM DESIGN DESCRIPTION

The holders would be cylindrical-shaped with outside diameters of 7.6 centimeters (3 inches) and would occupy the centers of the target holders. The targets themselves would reside inside each of these cylinders. The targets would be solid plates that contain target powder and a small volume of liquid or a larger volume that contains a compressed gas. The beam line would have vacuum isolation foil, which would separate the helium-cooling chamber from the cyclotron beam line. The vacuum isolation foil would be 0.0038-centimeter-thick (0.0015-inch-thick) aluminum alloy. The helium chamber would provide the reservoir for the chilled helium that would be passed over the front surface of the target foil. Should a window failure occur, the design of the window and its mounting structures must provide for effective operation and ease of replacement. Capturing the window in a foil holder that would be inserted between the beam line and the helium cooling assembly would satisfy these requirements. The front foil of the target must be thick enough to withstand the pressure generated inside the target during irradiation, which can be more than 600 pounds per square inch. In back of the target chamber there would be a water cooling assembly that would help remove heat from the target body.

Radioisotopes can be removed from this target cave in two different ways. The first of these would be used for the solid targets. The target plate containing the irradiated powder would be remotely removed from the target body and placed into a shielded container. This container would be rolled out of the facility and transported to a hot laboratory. Once at a hot laboratory, the target would be processed to extract the desired radioisotope.

The second method of target extraction would be through a processing station in the target vault. In this method, the fluid target contents would be pushed out of the target with a stream of helium and onto a resin or absorbent column that would retain the desired radioisotope. This column then would be transported to a hot laboratory.

F.1.2.2.3 Research Radioisotope Production—Southeast Target Cave

SYSTEM FUNCTION

The isotope production equipment would include several components: the target holder (with target), the water cooling system, and the helium cooling system for the front foil of the targets. Collectively, these systems must provide for target irradiations in safe, cost-effective and environmentally conscious manners.

SYSTEM DESIGN BASIS

The system would be designed to accept a proton beam with a nominal energy of 70 million electron volts and a maximum average beam current of 1 milliampere. Cross-section-type experiments would be expected to use only 1 to 10 microamperes of beam current but target research may use up to 1 milliampere. Target shielding would be sized to accommodate up to 1 milliampere of beam current, since the cyclotron would be capable of delivering currents of up to 2 milliamperes.

The operations sequence breaks down into four major operations: (1) load targets, (2) irradiate targets, (3) extract targets, and (4) transport irradiated targets.

Load Targets

Target irradiation would occur in the southwest target cave in an automated target changer assembly. Access to the target chamber would be through the maze originating on the west side of the facility. The fluid targets would be loaded remotely from gas or liquid reservoirs residing in the target cave. The solid targets would be prepared outside the facility and brought in and placed in the target holder.

Irradiate Targets

The first steps in preparing to start an irradiation run after the target stack has been loaded would be to establish coolant flow. This would be done in a two-step process: first by starting flow in the water system and then by evacuating and then pressurizing the helium system, followed by circulation initiation. The beam can be delivered to the target when the cooling system is functioning properly and all interlocks are satisfied. Irradiation would be continuous as long as the systems performance indicators, such as flow indicators and temperature monitors, remain within specified limits. The beam current striking the target would be integrated to determine when the proper number of protons has struck the target and the irradiation is complete.

Extract Targets

A transfer rabbit would be in place inside the target cave, which would hold the resin column or absorbent used to extract the desired radioisotope from the target material. The first step in preparing to extract the irradiated target material would be to stop the coolant flows. The target material would be forced out of the target and onto the resin column with a flow of helium. Once the radioactive isotopes have been transferred to the column, the flow of helium would be stopped and the transfer rabbit dropped into the transfer tube.

Transport Irradiated Targets

The transfer rabbit would be dropped into a transfer tube and pneumatically sent to a hot laboratory.

F.1.3 Facility Systems Design

The physical layout of the new cyclotron building would consist of two levels. The first floor (**Figure F–3**) would contain the vault room that would house the 70-million-electron-volt cyclotron, beam transport systems, cyclotron mechanical room, four target rooms, and storage room. The cyclotron vault room would be centrally located with a high bay equipped with a 15-ton bridge crane. There would be concrete trenches in the floor between the target rooms and the cyclotron vault room and a cross-shaped floor trench beneath the cyclotron. These trenches would be lined with an epoxy coating, which acts as secondary containment for any liquid that may be spilled, and have leak-detection sensors to comply with local environmental regulations. The cyclotron vault room would have concrete ceiling with a removable roof plug for overhead installation of the cyclotron. The second floor would consist of a transfer room, staging area, and electrical and mechanical room. The transfer room would contain a concrete hot cell connected to the target room located directly below. Materials would be transferred from the hot cell to a shielded cask and transported to the hot side of the building for processing.

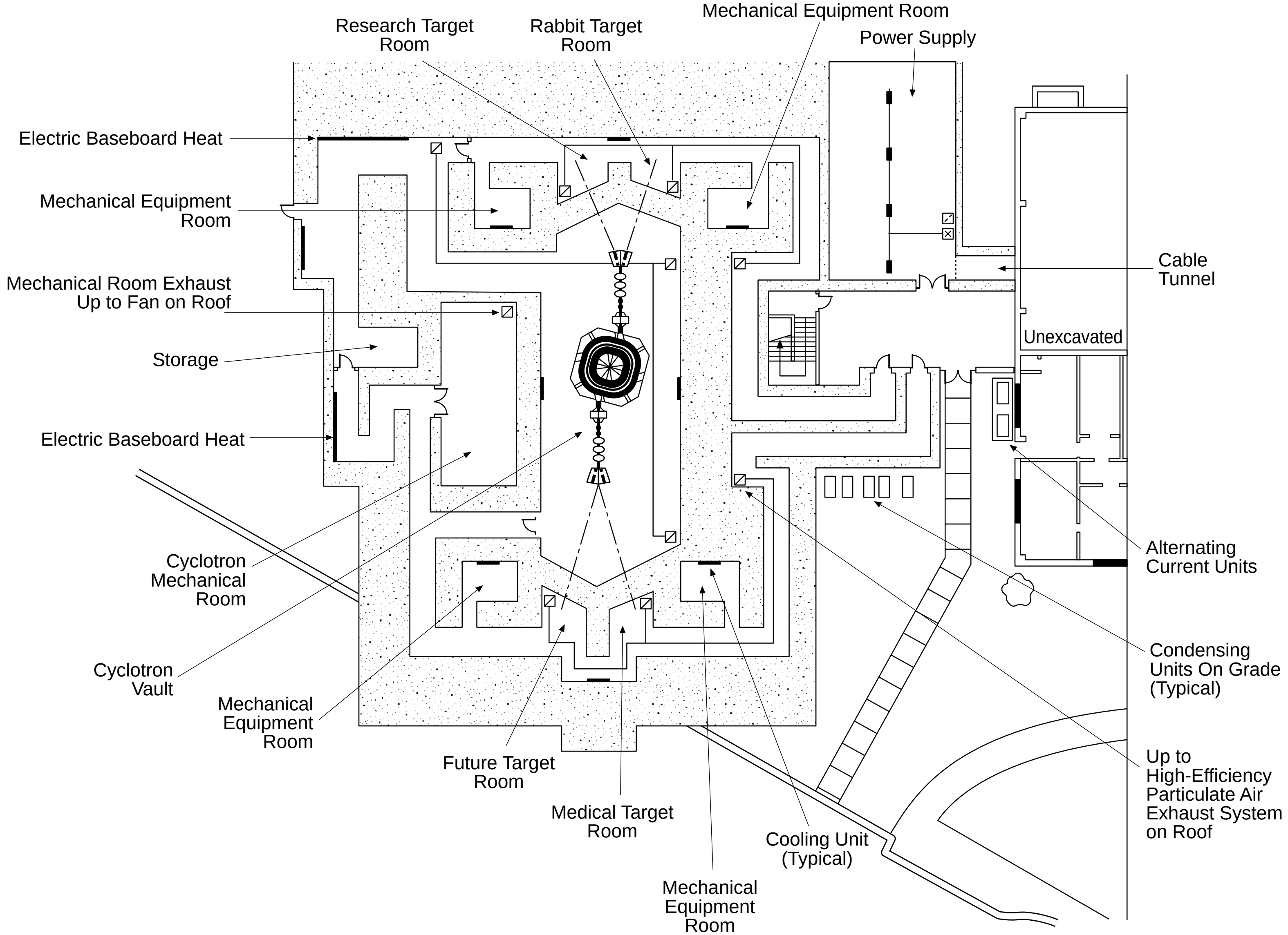
F.1.3.1 Architectural and Structural Design

F.1.3.1.1 First-Floor Cyclotron Facility

The interior spaces on the first floor would include the cyclotron vault, the cyclotron mechanical room, four target rooms with individual mechanical and electrical rooms, and a power supply room.

SYSTEM FUNCTION

The cyclotron vault would be surrounded by perimeter shielding walls that are 4.6 meters (15 feet) thick with a 0.91-meter-thick (3-foot-thick) ceiling constructed of reinforced concrete. All other interior spaces would have a minimum shielding of 1.5 meters (5 feet) of concrete. The 15-ton bridge crane would be used for handling shield components in the cyclotron vault. The lower floor would be approximately 42.7 by 41.1 meters (1,755 square meters) [140 by 135 feet (18,900 square feet)], partially below grade. The first floor would house the cyclotron, target rooms, and cyclotron power supply room. The interior ceiling heights would be 5.8 meters (19 feet) for the cyclotron vault, and a minimum of 2.7 meters (9 feet) for all other spaces. The entire first floor facility would be constructed of reinforced cast-in-place concrete faced with brick veneer. The function of the structural systems would be to provide the support for the structures to resist all anticipated loads from the soil and the second-floor facility and all loads produced from the mechanical and electrical utilities within the facility. Floors would be constructed of epoxy-coated concrete.



Source: TechSource 2000.

Figure F–3 Cyclotron Facility Floor Plan

SYSTEM DESIGN BASIS

The following is a generalized list of anticipated loads imposed on the first-floor cyclotron facility:

- Roof load: soil pressure, second-floor facility, and construction equipment load
- Floor load: live load of 250 pounds per square foot, 1,000-pound point load, target shield cube of 240 tons
- Wall load: lateral soils pressure of 55 pounds per square foot per foot of depth
- Wind load: not applicable
- Seismic load: design-basis-earthquake peak horizontal ground acceleration of 0.2 g

SYSTEM DESIGN DESCRIPTION

The following is a generalized list of descriptions of systems on the first-floor cyclotron facility:

- Roof system: .91-meter-thick (3-foot-thick) reinforced cast-in-place concrete
- Wall system: 4.6-meter-thick (15-foot-thick) reinforced cast-in-place concrete
- Foundation system: 3-foot-thick reinforced concrete mat footing
- Lateral resisting system: reinforced concrete shear walls with a concrete roof diaphragm
- Crane: the cyclotron high-bay facility would include a 15-ton bridge crane for loading and unloading the magnets; the concrete walls would support this crane

F.1.3.1.2 Second-Floor Cyclotron Facility

The interior spaces for this floor include the transfer room containing a concrete hot cell, the electrical mechanical room for the building, and a staging area. This partial second-floor structure would be constructed of a steel frame with concrete block and brick veneer walls and partitions, with a built-up roof system on a metal roof deck. The mechanical and electrical room would contain the main electrical service switchboards, panel boards, and mechanical equipment used for cooling the magnets, the target below, and the building itself. There would be a 5-ton bridge crane located on the second floor of the cyclotron facility to service the hot cell and target components.

SYSTEM FUNCTION

The second floor would consist of one structural area, approximately 30.5 by 40 meters (1,220 square meters) [100 by 130 feet (13,000 square feet)], and would house the transfer room, staging area, and major utility space. The entire second-floor facility would be constructed of reinforced cast-in-place concrete floors and a steel frame with masonry walls faced with brick veneer. The function of the structural systems would be to provide the support for the structures to resist all anticipated roof and wind loads and all loads produced from the mechanical and electrical utilities within the facility. Floors would be constructed of epoxy-coated concrete.

SYSTEM DESIGN BASIS

The following is a generalized list of anticipated loads imposed on the second floor cyclotron facility:

- Roof load: live load of 30 pounds per square foot
- Floor load: live load of 250 pounds per square foot, hot cell of 83 tons
- Wind load: the design-basis wind would be a straight wind at 90 miles per hour
- Seismic load: the design-basis earthquake peak horizontal ground acceleration of 0.20 g

SYSTEM DESIGN DESCRIPTION

The following is a generalized list of descriptions of systems on the second-floor cyclotron facility:

- Roof system: a built-up roofing system on a metal roof deck screwed to steel purlins that are welded to steel channel roof purlins
- Wall system: steel columns and girders with masonry infill walls running horizontally at the perimeter of the building
- Floor system: reinforced concrete under the steel columns; a mat footing approximately 30.5 centimeters (12 inches) thick would be incorporated under the hot cell, and 15.2-centimeter-thick (6-inch-thick) reinforced-concrete slabs on grade would be incorporated throughout the rest of the facility
- Lateral resisting system: a steel-braced frame with a metal roof diaphragm
- Crane: a 5-ton bridge crane installed over the hot cell

F.1.3.1.3 Hot Cell

There would be a hot cell on the second floor of the facility located above the northwest target cave that would contain the top of the target after-shaft and the target drive assembly. The hot cell would provide radiation shielding to safely handle the highly activated targets during target insertion and removal operations. It would also provide prompt neutron shielding above the target cave. Although the hot cell area would be an exclusion zone with the beam on, the presence of the hot cell would help reduce “sky shine” outside the target transfer room to acceptable levels for uncontrolled access.

The hot cell would be made from cast concrete and steel components. The concrete thickness would be determined based on criteria that the maximum personnel exposure rate from the highest likely radiation source term in the interior not exceed 5 millirem per hour. The interior dimensions would be adequate to perform operations such as target insertion and removal, simple repair of the target holder, and installation of an interior lead storage cave. The hot cell would have a viewing window fabricated of sheets of lead glass using standard construction techniques. The effective shielding thickness would be equal to that of the walls. The size would be sufficient to allow operators to see most of the interior and perform all required functions. Two master-slave remote manipulators would be provided for remote target handling operations. They would be sized to reach the entire working area of the hot cell.

The hot cell would have a shielded port hole mounted in a side wall to enable the removal of radioactive targets and radioactive waste. A shutter plug constructed from lead and steel would be planned. The location and arrangement of this hot cell opening would prevent direct radiation shine from hot cell contents into the target transfer room. The port hole design would be compatible with an existing target transport cask. The transport cask would be moved from this hot cell to the hot cell in the Target Processing Laboratory of the building by an electrical pallet truck. The port hole also would allow the introduction of small materials and equipment into the hot cell. In order to allow larger equipment to be introduced or removed for repair, a larger lead and steel shielded door also would be provided in a side wall. This door would be large enough for personnel entry for major maintenance or decontamination operations. Suitable locks would be provided to restrict such access unless entry would be permitted.

Other small penetrations would be provided for typical services in a serpentine manner to minimize straight line radiation paths. The hot cell would be connected to a high-efficiency particulate air-filtered ventilation system that would keep the interior pressure slightly negative with respect to the room. This would assure that no radioactive contamination would spread outward. The hot cell would be equipped with high-intensity lighting to ensure adequate vision through the thick lead-glass window. Standard 120-volt alternating-current electrical receptacles, water, and air would be supplied into the hot cell interior.

F.2 HIGH-ENERGY ACCELERATOR

F.2.1 Overview

F.2.1.1 System Description

In accelerator production of plutonium-238, an energetic beam of protons generated by a linear accelerator would be transported to a heavy metal target where spallation neutrons would be produced, and would be moderated in a surrounding blanket. The blanket would contain neptunium-237, which would capture the slowed neutrons to produce plutonium-238 through the same nuclear sequence as occurs in a reactor. The accelerator would be housed in a concrete tunnel, buried below ground to provide radiation shielding for operating personnel. A building housing radio frequency power systems and other equipment used to drive, monitor, and control the accelerator would be located above ground close to the accelerator tunnel. The target/blanket assembly would be housed inside a steel and concrete shield located within a multistory building that would contain appropriate service equipment. At the target, the small-diameter proton beam transported magnetically from the accelerator would be converted to a much larger cross section by a beam expander to reduce the power density to acceptable levels for the target cooling systems.

Figure F–4 shows the accelerator production of plutonium plant layout.

F.2.1.2 Plutonium-238 Production Process

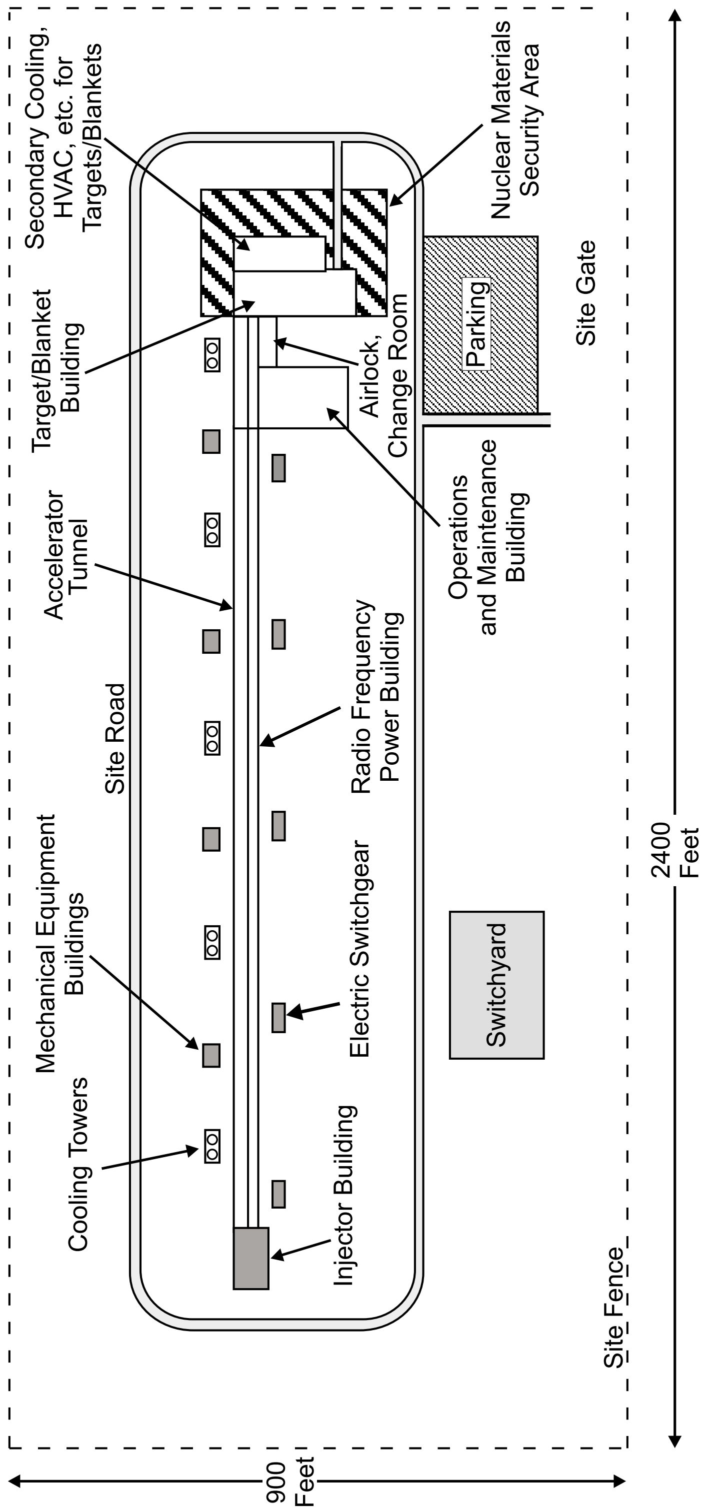
An accelerator-driven spallation-neutron source can be used to produce plutonium-238 from neptunium-237 feedstock through the capture and decay nuclear processes. A 1,000-million-electron-volt proton beam produced by a radio frequency linear accelerator would bombard a heavy metal (uranium-238) target, with each proton producing about 40 neutrons. Surrounding the spallation target would be a blanket containing a mixture of neptunium-237 and water coolant in an aluminum structure, all inside a beryllium reflector. The combination of materials in the target/blanket assembly would moderate the neutron spectrum down to thermal energies, where the capture cross section in neptunium-237 would be about 200 barns. As in a reactor, the nuclear reactions would be:

$$\text{Np237} + \text{n} \longrightarrow \text{Np238}$$

$$\text{Np238} \longrightarrow \text{Pu238} + \gamma$$

Plutonium-238 nuclei, once formed, would have a significant cross section for destruction through neutron capture, which must be taken into account when optimizing the blanket neutron spectrum, the neutron flux at the neptunium-237 locations, and determining the optimum length of the irradiation periods.

The use of medium-energy proton beams for nuclear material production or conversion is a well-established concept, going back several decades. The technology basis for high-energy proton accelerators and spallation neutron sources has over the past 10 years, been developing through two projects. One is the DOE Defense Programs development of a backup tritium production method, namely the Accelerator Production of Tritium program, and the other is the design of high-power pulsed spallation sources in the United States (the Oak Ridge Spallation Neutron Source facility), as well as in Europe and Japan.



HVAC Heating, Ventilating, and Air Conditioning

Source: TechSource 2000.

Figure F–4 Plant Layout for the Accelerator Production of Plutonium

In the spallation process, the high-energy protons smash into nuclei of the target material, initiating an intranuclear cascade followed by an evaporation process in which many neutrons are emitted. The spallation neutron spectrum would be similar to a fission spectrum, peaking at 1.2 million electron volts, but has a high-energy tail.

An important factor in the selection of proton beam energy and current is the dependence of the number of spallation neutrons produced on the beam energy. While there is a nearly linear relationship over a large energy range (up to 2 giga-electron volts), there is also a finite energy threshold (about 200 million electron volts), below which neutron production is effectively zero. The existence of this threshold energy means that neutron production as a function of beam power rises steeply for the first few hundred million electron volts, but asymptotically reaches a constant at high energies.

Several high-Z materials are potential target-material contenders, but depleted uranium would be the obvious choice for plutonium-238 production, since it produces more neutrons (by a factor-of-two) per incident proton than tungsten (the target material used in the Accelerator Production of Tritium), tantalum, or lead. The additional neutrons are produced by fast fission of uranium-238 nuclei induced by a fraction of the spallation neutrons.

F.2.1.3 Production Requirements

A preliminary target/blanket design has been developed for scoping purposes, based on the architecture employed in the Accelerator Production of Tritium target/blanket design. It would use uranium-238 (cooled by deuterium) as the neutron-production target. The target would be surrounded by a blanket of neptunium-237 in a dilute mixture of aluminum and water coolant. Enclosing the blanket would be a beryllium reflector. Initial code calculations show that, with 72 kilograms (158.7 pounds) of neptunium-237 in the blanket, about 40 neutrons would be produced by each proton, of which about 60 percent would be captured in neptunium-237 to produce plutonium-238. Further optimization may increase both the number of neutrons per proton and the fraction useful for making plutonium-238 nuclei, but improvements greater than a factor of 1.3 in the number of plutonium-238 nuclei made by each proton are unlikely.

Once produced, the plutonium-238 nuclei are subject to destruction processes as long as they remain in the neutron flux. The dominant process is Pu238 + n --> Pu239 + γ, which has a 540-barn thermal cross section, significantly greater than the 200 barn cross section for plutonium-238 production. Calculations made show that there is an optimum neutron flux and irradiation campaign period that minimizes plutonium-238 destruction without invoking an excessive frequency of blanket reloading cycles. For example, at a flux of 4×10^{13} per square centimeters, the fractional plutonium-238 destruction in 90 days would be 6.7 percent.

The annual production requirement for plutonium-238 for this NI PEIS has been given as 5 kilograms (11 pounds). Assuming 20 percent losses in chemical processing, 6 kilograms (13.2 pounds) per year would be needed in the material extracted from the production blanket. The year would be divided into three 4-month production campaigns, with a net amount of 2 kilograms (4.4 pounds) of plutonium-238 produced in each, allowing for the fraction destroyed. Each campaign would be divided into 100 days of production and 21 days for recycling the production blanket. A 90 percent plant availability during the scheduled operating periods is assumed, which should be achievable based on operating experience at the Los Alamos National Laboratory linear accelerator. Then the average proton current required as a function of beam energy is determined by the production relationship:

$$M/(1 - 0.067) = 6.24 \times 10^{18} \times I(E) \times Y(E) \times 238 \times 1.67 \times 10^{-27} \times 0.90 \times 0.854 \times 10^{7}$$

$$M = 17.75\ I(E)Y(E),$$

where M is the mass of plutonium-238 required per campaign in kilograms, I(E) is the average proton current in amperes, and Y(E) is the yield of plutonium-238 nuclei per incident proton. With M = 2 kilograms, this becomes

$$I(E) = 0.113 / Y(E).$$

At a beam energy of 1,000 million electron volts, the preliminary target/blanket neutronics show that about 24 plutonium-238 nuclei are produced by each proton, setting 4.7 milliamperes as the nominal average current requirement.

F.2.1.4 Accelerator

As a stand-alone machine, a reasonable design basis for a plutonium-238 production accelerator would be a pulsed normal-conducting linac having an architecture similar to that of the January 2000 (baseline) normal-conducting linac design for the Oak Ridge Spallation Neutron Source facility. The normal-conducting version of the Spallation Neutron Source linac has a 1,000-million-electron-volt beam energy, and an average output current of 2 milliamperes, about one-third the requirement for plutonium-238 production. The peak current would be 36 milliamperes, corresponding to a beam duty factor of 0.056. However, the Spallation Neutron Source linac design was intended to be directly upgradeable to a 4.0-milliamperes average current by doubling the peak current to 72 milliamperes. For the plutonium-238 production linac scoping design, this step also would be taken and the duty factor would be stretched to 0.066 to provide the required average current. Since the radio frequency power systems in the Spallation Neutron Source machine are designed for up to 0.09 duty factor, the same kind of power stations could be used for the plutonium-238 production linac. This modified version of the Spallation Neutron Source linac would satisfy the beam power requirement for plutonium-238 production and seems a reasonable model for carrying out the estimates needed for the proposed mission.

The plutonium-238 linac concept would begin with an H^+ injector supplying beam to a 6-million-electron-volt radio frequency quadrupole operating at 400 megahertz. The Spallation Neutron Source machine uses a H^- beam instead of protons, and has complex chopping arrangements at the front end. However, both of these features pertain to injection into a storage ring following the linac and can be eliminated in the plutonium-238 production application, allowing considerable simplification. The radio frequency quadrupole would be followed by a 400-megahertz drift-tube linac to 80 million electron volts, and an 800-megahertz coupled-cavity linac to full energy of 1,000 million electron volts. Accelerating structure lengths, gradients, focusing periods, and aperture sizes would be nominally the same as in the Spallation Neutron Source design. Beam dynamics simulations for the Spallation Neutron Source linac provide assurance of beam losses low enough (less than 0.1 nanoampere at 1,000 million electron volts) to permit unrestricted hands-on maintenance. The Spallation Neutron Source linac radio frequency power system employs high-peak-power klystrons (2.5 megawatts in the drift-tube linac, 5.0 megawatts in the coupled-cavity linac). Because the radio frequency efficiency (beam loading) of the Spallation Neutron Source linac would be relatively low (0.25), doubling the peak current as proposed above would increase the number of required radio frequency stations by a factor of only 1.25. However, because of the duty factor increase, each station would operate at a factor 1.18 higher average power. Key parameters for the reference accelerator are given in **Table F–1**.

Table F–1 Linac Parameters

Parameter	Radio Frequency Quadrupole	Drift-Tube Linac	Coupled-Cavity Linac	Total
Radio frequency (megahertz)	400	400	800	
Output beam energy (million electron volts)	6	80	1,000	1,000
Accelerating gradient (average) (megavolts per meter)	–	–	2.63	–
Average current (milliamperes)	4.7	4.7	4.7	4.7
Peak current (milliamperes)	72	72	72	72
Beam duty factor (milliamperes)	0.066	0.066	0.066	0.066
Radio frequency duty factor (milliamperes)	0.081	0.081	0.081	0.081
Output beam power (average) (megawatts)	0.03	0.38	4.7	4.7
Output beam power (peak) (megawatts)	0.45	5.76	71.2	71.2
Average cavity power loss (megawatts)	0.17	0.45	6.58	7.20
Radio frequency station peak power (megawatts)	2.5	2.5	5.0	–
Number of radio frequency stations (megawatts)	1	9	37	47
Radio frequency power delivered (peak) (megawatts)	2.0	12.9	165.2	180.3
Radio frequency power delivered (average) (megawatts)	0.15	0.95	12.2	13.3
Alternating current power for radio frequency (megawatts)	0.3	2.1	26.5	28.9
Alternating current for linac and high-energy beam transport (megawatts)	–	–	–	34.4
Section length (meters)	7	59	404	470

Key: Linac, linear accelerator.
Source: TechSource 2000.

Other accelerator options are possible, and might result in somewhat lower costs, coupled with superior performance. A reduced operating cost can be obtained by using super conducting accelerating cavities in the high-energy part of the pulsed linac, as in the Spallation Neutron Source final design. However, this introduces extra complications and results in somewhat higher capital costs. Using a linac with a lower beam-output beam energy (500 million electron volts) and higher current (14 milliamperes) would be another choice. Such a machine would employ super conducting cavities above 100 million electron volts, and could be somewhat more compact than the nominal Spallation Neutron Source linac. However, scoping cost estimates suggest that its capital costs would likely be not very different than for the reference 1,000-million-electron-volt pulsed linac.

Optimization of target/blanket performance as a function of beam energy, choice of materials and geometry, etc., has not been done. In concert with an analysis of accelerator costs as a function of proton energy (using models developed for the accelerator for production of tritium and other high-power linac projects), such an optimization might well lead to a plutonium-238 production system design with significantly improved performance and lower costs. In this connection, it should be noted that a multipurpose higher-power accelerator-driven system, in which the costs of producing the protons are shared between several nuclear missions, would result in much lower capital costs for plutonium-238 production, as well as lower operating costs. Such a system almost certainly would involve an accelerator with a beam current of 30 to 50 milliamperes, using a super conducting high-energy section, and suitable beam-sharing arrangements for the different missions.

F.2.2 Isotope Production Systems Design

F.2.2.1 Target Blanket Assembly

The spallation target portion of the reference target blanket assembly would be 28.4 centimeters (11.2 inches) wide by 28.4 centimeters (11.2 inches) high, and 100 centimeters (39.4 inches) long in the beam direction. It would consist of 504 kilograms (1,111 pounds) of depleted uranium packaged in 11 kilograms (24.3 pounds) of aluminum and contain 10 kilograms (22 pounds) of heavy water in its cooling channels. The target would require the removal of 4,360 kilowatts of heat due to fissions and 956 kilowatts due to gamma heating.

The blanket portion of the target blanket assembly would contain 72 kilograms (158.7 pounds) of neptunium-237 packaged in 1 kilogram of aluminum structure and would be cooled with 93 kilograms of light water. It would occupy a 5-centimeter-thick (2-inch-thick) layer wrapped around the four long sides and the down-beam end of the target. The side layers would extend 30 centimeters (11.8 inches) beyond the uncovered end of the target. The purpose of this extension would be to capture some of the neutrons that would emanate from the beam entrance face of the target. That face would be exposed because placement of feedstock in the proton beam would cause its demise by spallation. The blanket region would require the removal of 361 kilowatts of heat due to fissions and 966 kilowatts due to gamma heating.

Cooling water manifolds 2 centimeters (0.8 inch) thick and containing 25 kilograms of light water would cover the top and bottom surfaces of the target assembly. The total weight of the target assembly would be 716 kilograms (1,578 pounds). The weight of the dry assembly would be 588 kilograms (1,296 pounds).

F.2.2.2 Reflector Assembly

The reflector would consist of 30-centimeter-thick (11.8-inch-thick) beryllium slabs that would cover all but the beam-entrance face of the target. It would weigh 2.5 metric tons. The outer dimensions of the reflector would be 99 centimeters (39 inches) wide by 103 centimeters (40.6 inches) high, and 165 centimeters (65 inches) long in the beam direction.

F.2.2.3 Vacuum Tank and Internal Shielding

The target assembly would be positioned near the center of a vacuum tank that would be 6.1 meters (20 feet) diameter and 5.5 meters (18 feet) high. The target and reflector assemblies would be hung from the bottom of a shield plug that would be 1.0 meter (3.3 feet) wide, 1.7 meters (5.6 feet) long, and 2.4 meters (7.9 feet) tall. The top of the plug seals, and would be supported by, a penetration in the top lid of the tank. Cooling water and instrumentation lines would be routed from the target reflector assemblies, up through the plug, to the top of the tank.

The purpose of the large tank would be to allow space to install sufficient steel shielding so that the tank would not become activated. This would allow personnel to work on the plug at the top of the tank when the beam is off. It also would make it possible to use elastomers as seals for the plug and tank lid. It would greatly simplify tank removal when the facility is decommissioned.

The shielding within the tank would be 2.4 meters (7.9 feet) thick above and downstream of the target assembly, 2.0 meters (6.6 feet) below and upstream, and 2 meters (6.6 feet) to the sides.

The shielding to the sides of the plug and surrounding the target and reflector assembly would be movable to allow extraction of the plug and the assemblies hung from it.

F.2.2.4 External Shielding

An additional 3 meters (9.8 feet) of steel shielding, plus 1 meter (3.3 feet) of concrete, are wrapped around and over the tank to permit unlimited personnel access when the beam is on. Access to this region would be required to prepare for target blanket assembly change out and to prepare irradiated target blanket assemblies for disassembly in the hot cells.

A portion of the shielding directly above the tank would be mounted on rollers that would allow it to be rolled aside to provide easy access to the plug and its associated piping.

F.2.2.5 Beam Transport

The beam transport system would direct the proton beam from the accelerator onto a straight-ahead beam stop or bend it toward the target. The straight-ahead beam stop would be required for the commissioning and tune-up of the accelerator.

The beam transport system would consist of quadrupole magnets that would maintain the focus of the beam and dipole magnets that would bend the beam. The beam would travel inside a vacuum pipe that would be located within the magnets. Instruments, which would diagnose the location of the beam, would be positioned at strategic points within the beam transport line. A few very thick plugs would be located within the transport line, but would be held above the beam position. These plugs would be lowered to block passage of the beam as protection to workers in the very unlikely situation that a beam would be directed into the wrong area.

The beam line that would be bent toward the target would contain additional diagnostic and beam-steering components. This equipment would raster the proton beam back and forth across the front face of the target to provide uniform heating of the target.

A large-capacity vacuum pumping system would maintain the beam transport line and the target assembly at pressures in the microtor region.

F.2.2.6 Target Building

The building that houses the target would be a massive concrete structure with a 23- by 62-meter (75.5- by 203.6-foot) footprint. The beam stop and the target-assembly tank occupy about one-half of the building. The roof height at that location would be 27 meters (23 feet). The beam centerline has a 100-meter (328.4-foot) reference elevation. The roof would be at 121 meters (397.4 feet) and the floor would be at 94 meters (308.7 feet).

The building would be oriented so that the long side would be at right angles to the accelerator. The straight-ahead beam line runs parallel to the short side and would be 6 meters into the building from the end wall. The tune-up beam stop would be located on that line. The target assembly tank would be located 15 meters (49.3 feet) from the short wall (9 meters [29.6 feet] from the beam stop). The beam transport system bends the beam about 30 degrees to enter the tank. The tank rests on 3 meters (9.9 feet) of steel that would be stacked on the floor. Additional steel, and concrete, shielding surrounds the beamstop and tank. The top of the shielding would be 13 meters (42.7 feet) above the floor (elevation of 107 meters [351.4 feet]).

A remotely operable crane covers the large area of the deck. The crane hook rises 9 meters (29.6 feet) above the deck floor.

Three hot cells with 1-meter-thick (3.3-foot-thick) walls would be lined up in a row down the centerline of the first floor. The space on either side of the row of hot cells forms operating galleys for the remote-handling operations within the cells. The exterior wall of the galley floor would be indented under the operating deck. The indentation forms a truck unloading station. Large hatches over the station allow the crane hook to lift heavy loads from trucks into the operating deck

The hot cell closest to the tank houses the purification systems for the target assembly and beamstop water systems. The middle cell would be used for demounting the target assembly from its shield plug and for disassembling the irradiated target and packaging it for shipment.

The third cell would be used for general maintenance and repair. It would be also used for preparing a new target for installation, especially if old components were reused.

Hatches in the operating deck provide crane and remote-handling equipment access to several locations below the deck. Access would be provided to each hot cell and to several storage wells located within the massive beam stop and tank shielding. The primary-cooling systems, heavy water (deuterium oxide) for the target and light water (hydrogen oxide) for the blanket, would be also located under hatches in pits within the shielding.

The floor, exterior walls, and roof of the operating deck would be at least 1-meter-thick concrete, which provides both structural strength to the building and shielding from the radiation sources within the room during target transfers. All exterior penetrations for services would be sealed and all pipes and ducts contain valves, which permit the building to be sealed airtight if necessary in an accident situation.

F.2.2.7 Cooling Systems

The proton beam passes through thin layers of heavy water used to cool the uranium in the target. The neutrons and other particles that would be created in the uranium also pass through the heavy water and scatter outward and interact with the light water cooling the neptunium in the blanket. Particle interactions with the oxygen atoms of water create every isotope lighter than oxygen, and several that would be heavier. Of all the isotopes created, beryllium-7 would be particularly bad because of its energetic 500-kiloelectron volt gamma ray and relatively long half-life of 53 days. Calculations show that the proton beam alone creates 4.4×10^{13} beryllium-7 nuclei per second. Minute failures of the cladding would allow uranium and neptunium, and their fission fragments, to enter the cooling water.

This water would be a potential source of radioactive emissions; therefore, an intermediate water-cooling loop would be inserted between the water that cools the target and the water that flows through the air in the cooling towers. The three loops are known as primary, secondary, and tower.

The roles of the three cooling loops are:

- There would be two primary loops, one filled with heavy water to cool the target and the other filled with light water to cool the blanket and reflector. The components used in these loops would be shielded and provided with leak detectors. Ion exchange resin tanks used to remove impurities, including beryllium-7, would be located in shields. These two loops reject their heat to two primary heat exchangers. All the components of these two loops would be located in pits beneath the operating deck and would be designed to be remotely maintained and removed.

- The two primary heat exchangers would be cooled by the secondary cooling loop. All the components of this loop (except the primary heat exchangers) would be in a mechanical equipment room outside the shielded target building.

- The secondary loop heat exchanger would be cooled by water that flows through wet heat exchangers that reject the heat in the water to air.

The heat removal requirements for the two primary cooling systems would be heavy water cooling the target, 5.1 megawatts; and light water cooling the blanket and reflector, 1.3 megawatts.

Heat removal requirement for the secondary and tower cooling systems would be 6.4 megawatts.

F.3 REFERENCES

TechSource (TechSource, Inc.) 2000 *Nuclear Infrastructure PEIS Data Submittal for Accelerators*, Santa Fe, NM, June 29.